MAGNETIC MEDIA WITH IMPROVED EXCHANGE COUPLING

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Background of the Invention

This invention pertains to magnetic recording media such as magnetic disks.

Fig. 1 illustrates a magnetic recording medium 1 constructed in accordance with the prior art used for longitudinal data recording. Medium 1 comprises a substrate 2, an underlayer 3, a Co alloy magnetic layer 4 and a carbon protective overcoat 5. Also shown in Fig. 1 is a first region 4a of layer 4 magnetized in a first direction D1, a second region 4b magnetized in a second direction D2 opposite the first direction, and a transition region TR between regions D1 and D2. In magnetic recording, it is desirable for transition region TR to be as small as possible in order to maximize areal recording density. In general, the length of transition region TR is proportional to MrT/Hc, where Mr is the magnetic remanence of the Co alloy, T is the thickness of layer 4, and Hc is the coercivity of layer 4.

In order to reduce the length of region TR, one might be tempted to reduce MrT. Unfortunately, reducing MrT in medium 1 reduces the thermal stability of layer 4. In other words, reducing MrT reduces the ability of layer 4 to retain its magnetization state, and hence the data recorded in layer 4, as temperature increases. (Obviously, thermal stability is a highly desirable characteristic in a magnetic medium.)

1   Fig. 2 illustrates a second magnetic recording medium 20 in accordance with the

2   prior art comprising a substrate 22, an underlayer 24, a lower Co alloy magnetic layer 26,

3   a Ru layer 28, an upper Co alloy magnetic layer 30 and a carbon protective overcoat 32.

4   Medium 20 is designed to facilitate simultaneous reduction of the length of transition

5   region TR and increase in thermal stability. In particular, if Ru layer 28 has a thickness

6   within a certain range (e.g. 0.3 to 1.0 nm), magnetic layers 26 and 30 are

7   antiferromagnetically coupled to one another. Because of this, the length of transition

8   region TR for medium 20 is proportional to $Mr_{26}T_{26} - KMr_{30}T_{30}$, where K is a

9   proportionality constant, Mr_{26} is the magnetic remanence of layer 26, T_{26} is the thickness

10   of layer 26, Mr_{30} is the magnetic remanence of layer 30 and T_{30} is the thickness of layer

11   30. (Constant K is related to the degree of antiferromagnetic coupling between layers 26

12   and 30.)   However, the thermal stability of medium 20 increases as a function of

13   $Mr_{26}T_{26} + K_2Mr_{30}T_{30}$. Thus, while the antiferromagnetic coupling permits one to reduce

14   the length of transition region TR, it also improves thermal stability. (The

15   antiferromagnetic coupling also improves the signal to noise ratio of medium 20.)

16   When recording data in medium 20 of Fig. 2, because of the antiferromagnetic

17   coupling between layers 26 and 30, when one magnetizes a region within layer 30, e.g. as

18   shown by arrow D3, the magnetization direction of layer 26 is in the opposite direction,

19   e.g. as shown by arrow D4. Fig. 3 shows a hysteresis loop 40 for the structure of Fig. 2 if

20   layers 26 and 30 were strongly coupled. As can be seen, as one increases the applied

21   magnetic field H_{app} to medium 20, in portion P1 of hysteresis loop 40, both magnetic

22   layers 26 and 30 are magnetized in the same direction D3. As one reduces the applied

23   magnetic field H_{app} past point P2, the magnetization direction of layer 26 begins to switch

1   to direction D4. Portion P3 of hysteresis loop 40 shows the magnetic characteristics of

2   medium 20 as layer 26 changes magnetization direction in response to applied magnetic

3   field H_{app}. As applied magnetic field H_{app} is brought to zero (point P4), layer 26 is

4   magnetized in direction D4.

5   Fig. 4 shows a hysteresis loop of medium 20 if layer 26 were weakly

6   antiferromagnetically coupled to layer 30. As can be seen, the point P5 at which layer 26

7   switches magnetization direction (i.e. from direction D3 to D4) occurs at a much lower

8   applied magnetic field H_{app} in Fig. 4 than in Fig. 3. Weak coupling between layers 26

9   and 30 is disadvantageous because it increases the amount of time required to switch the

10   state of medium 20 to an antiferromagnetic state. In particular, it takes more time to

11   create a situation in which layer 30 is magnetized in direction D3 and layer 26 is

12   magnetized in direction D4. The magnetic recording medium relies on thermal energy to

13   switch the magnetization direction of layer 26 to direction D4. Further, weak coupling

14   can also create a situation in which layer 26 is not as completely magnetized as desired

15   when H_{app} is brought to zero.

16   It would be desirable to increase antiferromagnetic coupling between layers 26

17   and 30. One way to do this is to add pure Co layers 34 and 36 on each side of Ru layer

18   28, e.g. as provided in medium 20' shown in Fig. 5. Co layers 34 and 36 increase

19   antiferromagnetic coupling between layers 26 and 30. Unfortunately, Co layers 34 and

20   36 increase noise in medium 20' because of intergranular magnetic coupling in layers 34

21   and 36. It would be highly desirable to increase antiferromagnetic coupling between

22   layers 26 and 30 without suffering this increase in noise.

23

1   Summary

2   A magnetic recording medium in accordance with the invention comprises a

3   lower magnetic layer, an intermediate layer above the lower magnetic layer, and an upper

4   magnetic layer above the intermediate layer. The recording medium is typically a

5   magnetic disk. The upper and lower magnetic layers are ferromagnetic, and typically

6   comprise a Co alloy, a Fe alloy or a Ni alloy. The intermediate layer has the

7   characteristic that it induces antiferromagnetic coupling between the upper and lower

8   magnetic layers. In one embodiment, the intermediate layer comprises Ru.

9   In accordance with one aspect of the invention, the lower magnetic layer has a

10   high Ms in order to facilitate a high exchange field Hex. (The exchange field is a

11   measure of the amount of coupling between the upper and lower magnetic layers.) In one

12   embodiment, the Ms of the lower magnetic layer is greater than or equal to 250 emu/cm^3,

13   and typically greater than 300 emu/cm^3. The Ms of the lower magnetic layer can be less

14   than or equal to 2000 emu/cm^3 and generally less than or equal to 1400 emu/cm^3.

15   It has been discovered that the high Ms values cooperate with the Ru intermediate

16   layer to provide strong antiferromagnetic coupling. (It is believed that the reason that a

17   high Ms promotes antiferromagnetic coupling is that coupling is a function of the density

18   of spins available for transport across the Ru. The higher the Ms, the greater the spin

19   density, the higher the amount of exchange across the Ru.)

20   In accordance with another aspect of the invention, the relation between dynamic

21   coercivity Hc and the exchange field Hex is such that the lower magnetic layer will reach

22   its steady state magnetization condition after writing within one period of revolution of

23   the magnetic disk. In one embodiment, the lower magnetic layer will reach between 90

1   and 100% of its steady state magnetization condition within one period of revolution of

2   the magnetic disk. In another embodiment, the lower magnetic layer will reach between

3   95 and 100% of its steady state magnetization condition within one period of revolution

4   of the magnetic disk.

5   Hc of the lower magnetic layer is greater than or equal to zero but less than the

6   exchange field Hex at recording switching times. The Hc of the lower magnetic layer at

7   recording switching times is typically less than or equal to about one half of the exchange

8   field for recording times. This facilitates quickly switching the lower magnetic layer to

9   its desired magnetization direction. (The Hc of the upper magnetic layer at recording

10   switching times is typically substantially greater than the Hc of the lower magnetic layer

11   at recording switching times.)

12   In accordance with another feature of the invention, the anisotropy constant Ku of

13   the upper magnetic layer is greater than 0.5×10^6 ergs/cm^3 to provide good thermal

14   stability. In one embodiment, the Ku of the upper layer is greater than 1.0×10^6 ergs/

15   cm^3. (The Ku of the upper magnetic layer should not be so high as to hamper writing,

16   and is typically less than 10^7 ergs/cm^3.) The Ku of the lower layer can be smaller than

17   the Ku of the upper layer. For example, the lower magnetic layer can have a Ku of $1.0 \times$

18   10^4 ergs/ cm^3, 1.0×10^3 ergs/ cm^3, or even lower (but greater than or equal to 0 ergs/cm^3).

19   (A lower Ku for the lower magnetic layer facilitates a lower coercivity, which in turn

20   facilitates ease of switching the magnetization direction of the lower magnetic layer.)

21   In one embodiment, the lower magnetic layer is a Co based alloy comprising

22   between 5 and 20 at. % Cr, 0 to 6 at. % Ta, 0 to 10 at. % B and 0 to 10 at. % Pt. The

23   alloy can contain between 0 and 10 at. % X, where X is one or more other elements. In

1　one embodiment, X is one or more of Nb, Ta, Cu, Mo, W, V, Si, C, Pd, Ru, Ir or Y.

2　Preferably, this alloy exhibits a Ms, Hc and Ku as described above.

3　　　In one embodiment, the upper magnetic layer is a Co based alloy comprising

4　between 10 and 30 at. % Cr, 8 to 20 at. % Pt and 0 to 20 at. % B. The upper magnetic

5　layer can comprise between 0 and 10 at. % X, where X is one or more other elements. X

6　can be one or more of Nb, Ta, Cu, Mo, W, V, Si, C, Pd, Ru, Ir or Y. Again, preferably

7　the alloy exhibits a Hc and Ku as described above.

8　　　A magnetic recording medium in accordance with another embodiment of the

9　invention comprises two or more Ru interlayers (e.g. two, three or more interlayers), each

10　sandwiched between two magnetic layers. The uppermost magnetic layer has the same

11　characteristics as described above for the upper magnetic layer. The magnetic layers

12　below the Ru interlayers have the same characteristics as described above for the lower

13　magnetic layer.

14　　　Although the foregoing description refers to upper and lower magnetic layers,

15　either or both of the upper and lower magnetic layers can comprise a plurality of

16　sublayers of different compositions. Thus, for example, if the lower layer comprises a

17　plurality of sublayers, the effective composite Ms of the sublayers combined should be a

18　value as described above. Similarly, if the upper or lower layer comprises a plurality of

19　sublayers, the effective composite dynamic Hc (e.g. at recording times) and Ku of the

20　sublayers should be a value as described above.

21

Brief Description of the Drawings

Fig. 1 illustrates in cross section a first magnetic recording medium constructed in accordance with the prior art.

Fig. 2 illustrates in cross section a second magnetic recording medium constructed in accordance with the prior art comprising a Ru layer for facilitating antiferromagnetic coupling between upper and lower magnetic Co alloy layers.

Fig. 3 is a hysteresis loop for a magnetic recording medium if upper and lower magnetic layers were strongly antiferromagnetically coupled to one another.

Fig. 4 is a hysteresis loop for a magnetic recording medium if upper and lower magnetic layers were weakly antiferromagnetically coupled to one another.

Fig. 5 illustrates in cross section a third magnetic recording medium constructed in accordance with the prior art comprising a Co layer formed between magnetic Co alloy layers and a Ru layer.

Fig. 6 illustrates in cross section a magnetic recording medium constructed in accordance with a first embodiment of the invention.

Fig. 7 illustrates in cross section a magnetic recording medium in accordance with a second embodiment of the invention.

Fig. 8A illustrates the effect of H-Field Sweep Rate on MrT in a magnetic recording medium in which the lower magnetic film has an Ms of 300 emu/cm^3.

Fig. 8B illustrates the effect of H-Field Sweep Rate on MrT for a magnetic recording medium in which the lower magnetic film has an Ms of 550 emu/cm^3 and therefore a higher exchange field than that of Fig. 8A.

1   Fig. 9A illustrates the fundamental harmonic amplitude decay for a magnetic

2 recording medium in which the exchange field is about 300 Oe.

3   Fig. 9B illustrates the fundamental harmonic amplitude decay for a magnetic

4 recording medium in which the exchange field is about 2500 Oe.

5   Fig. 10 illustrates a magnetic recording medium constructed in accordance with

6 third embodiment of the invention.

7   Fig. 11 illustrates a magnetic recording medium constructed in accordance with a

8 fourth embodiment of the invention.

9   Fig. 12 illustrates a magnetic disk in accordance with the present invention

10 incorporated into a disk drive.

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12 Detailed Description

13   Referring to Fig. 6, a magnetic recording medium 100 in accordance with the

14 invention comprises a non-magnetic substrate 102, an underlayer 104, a lower magnetic

15 layer 106, an intermediate layer 108, an upper magnetic layer 110 and a carbon protective

16 overcoat 112. Substrate 102 can be an aluminum alloy substrate coated with an

17 electroless plated nickel-phosphorus alloy. Alternatively, substrate 102 can be glass,

18 glass-ceramic, or other appropriate material. (Typically, the above-mentioned layers are

19 formed on both the top and bottom surfaces 102a, 102b of substrate 102, but only the

20 layers on top surface 102a are shown for ease of illustration.)

21   Magnetic layers 106 and 110 are typically Co, Fe or Ni-based alloys. Layer 106

22 is typically between 2 and 8 nm thick, and layer 110 is typically 6 to 30 nm thick.

23 Intermediate layer 108 is typically Ru or a Ru alloy (e.g. consisting essentially of Ru).

1   (Layer 108 is typically between 0.3 and 1.0 nm thick.) For the case of Co alloys, layers

2   106 and 110 typically have a HCP crystal structure and a $11\bar{2}0$ orientation.

3   Underlayer 104 is typically Cr or a Cr alloy such as Cr-Mo. In one embodiment,

4   underlayer 104 comprises $Cr_{80}Mo_{20}$ (at. %), has a thickness of 10 nm, and a BCC crystal

5   structure.

6   As mentioned above, in accordance with one aspect of the invention, magnetic

7   recording medium 100 exhibits a high exchange field Hex. This is typically

8   accomplished (at least in part) by ensuring that magnetic layer 106 exhibits a high Ms,

9   preferably greater than or equal to 250 emu/cm^3, and typically greater than or equal to

10   300 emu/cm^3, and in one embodiment, greater than 350 emu/cm^3. Typically, the Ms of

11   layer 106 is less than 2000 emu/cm^3 and for the case in which layer 106 comprises

12   primarily Co, the Ms of layer 106 is less than about 1400 emu/cm^3. (While the lower

13   magnetic layer 106 can have a higher Ms than upper magnetic layer 110, upper magnetic

14   layer 110 typically has a higher magnetic moment MsT (magnetization times thickness)

15   than lower magnetic layer 106.)

16   Also as mentioned above, the coercivity Hc of layer 106 is typically greater than

17   or equal to zero but less than the exchange field Hex at recording switching times. The

18   recording switching time is the amount of time one exposes a point on the recording

19   medium to a write magnetic field. For the case of a magnetic disk in a disk drive during

20   recording, the recording switching time is approximately the amount of time it takes a

21   point on the spinning disk to travel the length of the head write gap. (Disks in currently

22   manufactured disk drives spin at a rate between about 4,000 and 15,000 rpm. This

23   corresponds to a period of rotation of 15 milliseconds to 4 milliseconds.) For disk drives

1 currently being produced, the switching time is about 10 ns. Coercivity is the strength of

2 the magnetic field applied to a magnetized region of a magnetic film that is required to

3 reduce the magnetization of that region to zero. (It is a measure of the field strength

4 needed to record data in the film.) Coercivity depends on the length of time one applies

5 the magnetic field to a region of the magnetic film. In other words, it requires a stronger

6 magnetic field to write to a magnetic film if the field is only applied to the film for a very

7 short time than if the field is applied to the film for a very long time. In one embodiment,

8 the coercivity of lower magnetic layer 106 at recording switching times is less than the

9 exchange field Hex of medium 100, and preferably less than or equal to one half of

10 exchange field Hex (e.g. for a recording switching time of 100 ns or less). Typically, the

11 above-mentioned condition holds true for switching times of 1 ns to 10 ns or less (or

12 generally between 100 picoseconds and 100 ns). This facilitates the switching of the

13 magnetization layer 106 to a direction opposite that of layer 110. (Optionally, the above-

14 mentioned coercivity condition may also hold true for other amounts of time that a write

15 field is applied to a region of medium 100.)

16 In one embodiment, upper layer 110 has a static coercivity greater than 3000 Oe

17 (but typically less than 10,000 Oe). Lower layer 106 has a static coercivity less than

18 2500 Oe (but typically greater than or equal to 0 Oe).

19 Upper layer 110 has a dynamic coercivity (e.g. for switching times of 10 ns or

20 less) between 6000 and 25,000 Oe. Lower layer 106 has a dynamic coercivity less than

21 2500 Oe (but typically greater than or equal to 0 Oe).

22 Magnetic layer 106 is typically a HCP Co alloy. In one embodiment, layer 106

23 has 5 to 20 at. % Cr, 0 to 6 at. % Ta, 0 to 10 at. % B, 0 to 10 at. % Pt, and the balance is

1   Co. For example, layer 108 can be $CoCr_{16}Ta_4$. (As used herein, $CoCr_{16}Ta_4$ means an

2   alloy comprising 16 at. % Cr, 4 at. % Ta, and the remainder Co.) Alternatively, layer 106

3   can have 0 to 10 at. % X, where X is one or more other elements, e.g. one or more of Cu,

4   Mo, W, V, Si, C, Pd, Ru, Ir or Y. Layer 106 can have a Ku greater than or equal to 1.0 x

5   10^4 ergs/cm^3, e.g. between 0.5 x 10^6 and 1.0 x 10^6 ergs/cm^3.

6   In an alternative embodiment, lower magnetic layer 106 can be another

7   magnetically soft material with intergranular decoupling, e.g. suitably modified NiFe

8   (permalloy), FeAlSi (sendust), CoTaZr, FeTaC, NiFeNb, CoFe, NiCrFe, NiV, CuNi,

9   FeRh or PtMn.

10   Magnetic layer 110 is also typically a Co alloy layer and has a high Ms. In one

11 embodiment, layer 110 has between 10 and 30 at. % Cr, 8 to 20 at. % Pt, 0 to 20 at. % B

12 and the balance Co. For example, layer 110 can be $CoCr_{15}Pt_{11}B_{11}$. Alternatively, layer

13 110 can also include 0 to 10 at. % X, where X is one or more other elements, e.g. one or

14 more of Nb, Ta, Cu, Mo, W, V, Si, C, Pd, Ru, Ir or Y. In one embodiment, layer 110 has

15 a high Ku, e.g. a Ku greater than about 1.0 x 10^6 erg/cm^3, e.g. between 1.0 x 10^6 and 1.0

16 x 10^7 erg/cm^3 to promote thermal stability. (The Ku of layer 110 is greater than that of

17 layer 106.) Layer 110 also has a high Ms, e.g. greater than 300 emu/cm^3. In one

18 embodiment, layer 110 has a Ms between 300 and 650 emu/cm^3.

19   Figs. 8A and 8B illustrate the effect of H-Field Sweep-Rate on MrT for magnetic

20 recording media with lower and higher Ms, respectively. In particular, the H_{app}-field

21 sweep rate for Figs. 8A and 8B varied between 0.1 seconds to several seconds. The

22 magnetic disk of Fig. 8B had a lower magnetic layer exhibiting an Ms of about 550/cm^3.

23 Because of this, antiferromagnetic coupling between the upper and lower magnetic layers

1 was relatively high, and the lower magnetic layer generally switched magnetization

2 directions before the applied field H_{app} reached 0 Oe. In other words, Mr was generally

3 independent of the sweep rate.

4 In contrast, the lower magnetic layer of Fig. 8A had a lower Ms (300 emu/cm^3)

5 and thus exhibited less antiferromagnetic coupling. Therefore, in the context of the

6 magnetic medium of Fig. 8A (with a lower level Hc close to the exchange field strength),

7 Mr was more dependent on sweep rate—an undesirable characteristic because it does not

8 allow the lower layer to switch quickly to the desired state.

9 Figs. 9A and 9B illustrate the fundamental harmonic amplitude decay for

10 magnetic recording media with an exchange coupling field Hex of 300 Oe and 2500 Oe,

11 respectively. The Y axis of Figs. 9A and 9B represents the normalized fundamental

12 harmonic amplitude. In other words, after data is recorded in the magnetic recording

13 medium, the amplitude of the recorded signal is repeatedly read back. The Y axis

14 represents subsequent read-back values divided by the initial read-back value. Data in

15 Fig. 9A was generated for different data recording densities. As can be seen, the extent

16 to which amplitude dropped over time was highly dependent on recording density. For

17 example, for a density of 3 kFCI (3000 flux changes per inch), over a 20 second time

18 period, the normalized fundamental harmonic amplitude dropped to approximately 0.73,

19 whereas for a density of 289 kFCI, the normalized fundamental harmonic amplitude only

20 dropped to a value of about 0.98 after 20 seconds. The reason for this difference is that

21 the demagnetizing field increases as recording density increases (i.e. as the size of a

22 magnetized region decreases). This demagnetizing field helps to switch the

23 magnetization direction in lower magnetic layer 106. If the demagnetizing field is small

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1 (as in the case of a low recording density), it provides less assistance in switching the

2 magnetization direction of magnetic layer 106, and therefore it takes magnetic layer 106

3 more time to settle into a final magnetization state (i.e. magnetized in direction D4).

4   As mentioned above, the data of Fig. 9A was generated for a disk exhibiting

5 relatively low antiferromagnetic coupling between the upper and lower magnetic layers,

6 e.g. for an exchange field of about 300 Oe. In Fig. 9B, the disk exhibited relatively high

7 antiferromagnetic coupling between the upper and lower magnetic layers, i.e. about 2500

8 Oe. This relatively high coupling promotes switching of the magnetization direction of

9 the lower magnetic layer 106. Therefore, even for fairly low recording densities (e.g. 3

10 kFCI), the normalized fundamental harmonic amplitude after 20 seconds is about 0.91,

11 compared to 0.73 for Fig. 9A. A significant change in normalized fundamental harmonic

12 amplitude is undesirable because it means that medium 100 may exhibit inadequate

13 switching and signal stability.

14   Fig. 7 illustrates a magnetic recording medium 100a constructed in accordance

15 with another embodiment of the invention. Medium 100a is similar to medium 100 of

16 Fig. 6, but includes an optional seed layer 105 formed between underlayer 104 and lower

17 magnetic layer 106. Seed layer 105 can be as discussed in U.S. Patent 6,150,015, issued

18 to Bertero et al. on November 21, 2000, incorporated herein by reference.

19   Also shown in Fig. 7 is a magnetic layer 120 formed on magnetic layer 110.

20 Magnetic layer 120 enables one to tailor medium 100a with enhanced flexibility so that it

21 exhibits desired Hc, MrT, noise or PW50. In the embodiment of Fig. 7, layer 120 can be

22 10 nm thick, and can comprise $CoCr_{24}Pt_{12}B_8$, while layer 110 can be 6 nm thick and

1 comprise $CoCr_{15}Pt_{11}B_{12}$. Alternatively, magnetic layer 120 could comprise another alloy

2 such as CoCrPtTaB, other Co alloys, a Ni alloy or a Fe alloy.

3   Fig. 10 illustrates a magnetic recording medium in accordance with another

4 embodiment of the invention. In Fig. 10, a medium 100b comprises substrate 102, a 8

5 nm thick $Cr-Mo_{20}$ underlayer 104, a 2 nm thick $CoCr_{25}Ta_2$ seed layer 105, a 4 nm thick

6 $CoCr_{16}Ta_4$ magnetic layer 106, a 0.8 nm thick Ru intermediate layer 108, magnetic

7 sublayers 110a, 110b and 110c and a protective overcoat 112. Merely by way of

8 example, sublayers 110a, 110b and 110c can be 2 nm thick $CoCr_{16}Ta_4$, 6 nm thick

9 $CoCr_{23}Pt_{11}B_5Ta_1$ and 6 nm thick $CoCr_{15}Pt_{10}B_{12}$. In this embodiment, sublayers 110a,

10 110b, and 110c (which make up upper magnetic layer 110) are magnetized in a first

11 direction, while lower magnetic layer 106 is magnetized in a second direction opposite

12 the first direction by virtue of antiferromagnetic coupling resulting from intermediate

13 layer 108. Thus, it is seen that the upper magnetic layers can comprise a plurality of

14 sublayers. In an alternative embodiment, lower layer 106 can also comprise a plurality of

15 sublayers.

16   In this patent, the term "layer structure" will refer to a structure comprising one

17 layer or a plurality of layers that are ferromagnetically coupled to one another. Thus, as

18 used herein, lower layer 106 is a layer structure, and layers 110a, 110b and 110c

19 collectively are a layer structure.

20   Fig. 11 illustrates a medium 100c comprises a lowermost magnetic layer 106', a

21 lower Ru layer 108', a magnetic layer 106", a Ru layer 108" an uppermost magnetic layer

22 110 and a protective overcoat 112. For the embodiment of Fig. 11, the magnetic

23 characteristics of layer 110 are as described above for the embodiments of 6, 7 and 10.

1   Ru layers 108' and 108" are typically between 0.3 and 1.0 nm thick, and facilitate the

2   above-described antiferromagnetic coupling phenomenon. Layers 106' and 106" have

3   the same magnetic characteristics as those described above for layer 106 in the

4   embodiments of Figs. 6, 7 and 10. If one writes data in layer 110 such that the

5   magnetization direction is D5 and then removes the applied write magnetic field H_{app}, the

6   magnetization direction in layer 106" will be direction D6, which is in the opposite

7   direction of D5. The magnetization direction in layer 106' will be direction D7, which is

8   the opposite of direction D6.

9   While Fig. 11 shows two Ru layers 108', 108" sandwiched between magnetic

10 layers, in other embodiments, three or more Ru layers can be provided, each sandwiched

11 between magnetic layers. The benefit of this embodiment is to create greater thermal

12 stability in medium 100c.

13   In the embodiments of Figs. 6, 7, 10 and 11, the magnetization direction in layer

14 106 (or layers 106' and 106" for the case of Fig. 11) is controlled by the magnetization

15 direction in layer 110. In particular, layer 110 is antiferromagnetically coupled to layer

16 106 (or to layer 106" for the case of Fig. 11) and the magnetization in layer 110 forces

17 layer 106 (106") to assume a magnetization direction that is opposite to the direction of

18 layer 110. Similarly, the antiferromagnetic coupling between layers 106' and 106" cause

19 layer 106' to have a magnetization direction that is opposite to the magnetization

20 direction of layer 106". In effect, the magnetization directions for layers 106, 106' and

21 106" are determined by the magnetization direction of layer 110. Thus, it can be said that

22 layers 106, 106' and 106" are "slave layers", i.e. layers whose steady state magnetization

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1   direction (after the write field has been removed) is determined either directly or

2   indirectly by a "master layer", e.g. layer 110.

3   Magnetic recording media in accordance with the invention are typically

4   manufactured using a vacuum deposition technique such as sputtering. For example, one

5   or more substrates can be placed in a substrate carrier that carries the substrates past a set

6   of sputtering targets to deposit the various layers of the magnetic disk. The targets have

7   compositions that are substantially the same as the composition of the layers that they are

8   used to produce. Sputtering is typically accomplished in an atmosphere comprising an

9   inert gas such as argon. (Other gases may be present in the sputtering chamber as well.)

10   A magnetic medium in accordance with the invention (e.g. medium 100, 100a,

11   100b or 100c) is typically in the form of a disk incorporated within a disk drive, e.g. disk

12   200 drive 201 (Fig. 11). Disk drive 201 comprises magnetic disk 200 mounted on a

13   spindle 202 which is coupled to a motor 204 for rotating disk 200. A pair of read-write

14   heads 206a, 206b are positioned proximate to disk 200 for reading data from and writing

15   data to magnetic layers on each side of disk 200. Heads 206a, 206b are mounted on

16   suspensions 208a, 208b, which in turn are mounted on actuators (e.g. rotary or linear

17   actuators 210a, 210b) for moving heads 206a, 206b over desired data recording tracks of

18   disk 200. Although only one disk 200 is shown in drive 201, drive 201 can contain

19   multiple disks.

20   While the invention has been described with respect to specific embodiments,

21   those skilled in the art will recognize that changes can be made in form and detail without

22   departing from the spirit and scope of the invention. For example, the disk substrate can

23   be textured, e.g. using mechanical, chemical, and/or laser texturing techniques. Different

1   types of protective overcoats (e.g. carbon, hydrogenated or nitrogenated carbon, or

2   zirconia) can be applied to upper magnetic layer 110. A lubricant can be applied to the

3   top surface of the disk (e.g. a perfluoropolyether lubricant). The various layers of the

4   magnetic disk can be formed by any of a number of deposition techniques, e.g. a vacuum

5   deposition technique such as sputtering. Different segregants can be added to one or

6   more of the magnetic layers to break exchange coupling between the grains, e.g. boron,

7   silica, alumina, zirconia, or other oxides such as tantalum oxide, cobalt oxide, etc.

8   Different magnetic layer thicknesses can be employed. Different aspects or features of

9   the invention can be practiced independently of one another. Accordingly, all such

10   changes come within the invention.